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4.8.0 Loss of All AC Power (Station Blackout)

Learning Objectives:

1. Define the term “station blackout.”
2. Describe the interim response by the NRC to the station blackout concern.
3. Describe the plant response necessary to mitigate the consequences of a station blackout using existing equipment.
4. Describe the regulatory requirements addressing the station blackout concern.
5. Describe the accident sequence that makes the loss of all alternating current (ac) power a major contributor to the total core damage frequency at some reactor plants.

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4.8.1 Background and Basic Electrical Distribution Design

The General Design Criteria (GDC) in Appendix A of 10CFR50 establish the necessary design, fabrication, construction, testing and performance requirements for structures, systems, and components important to safety; these are the structures, systems and components that provide reasonable assurance that the facility can be operated without undue risk to the health and safety of the public. GDC 17, “Electric Power Systems,” requires that onsite and offsite electric power systems be provided to permit the functioning of structures, systems and components important to safety. These structures, systems, and components are required to remain functional to ensure that specified acceptable fuel design limits and design conditions of the reactor coolant pressure boundary are not exceeded as a result of anticipated operational occurrences, and that the core is cooled and containment integrity and other vital functions are maintained in the event of postulated accidents. GDC 17 specifies additional requirements for both the onsite and offsite electrical power distribution systems to ensure both their availability and reliability.

Figure 4.8-1 shows a typical offsite power system associated with a nuclear plant. During plant operation, power is supplied to the Class 1E (onsite) distribution system by the main generator. In the event of a unit trip, the preferred source of power to the onsite distribution system would be the offsite grid. If offsite power is available, an automatic transfer to the preferred power source ensures a continuous supply of ac power to equipment required to maintain the plant in hot standby and to remove decay heat from the core. If offsite power is not available due to external causes such as severe weather or equipment failure, the undervoltage condition sensed in the onsite distribution system initiates a transfer to the onsite (standby) power source. Figure 4.8-2 shows a typical onsite ac power distribution system. In the event that an undervoltage condition is sensed on the emergency buses following a unit trip, the system is designed to ensure the opening of all supply breakers to the buses, the disconnection of all unnecessary loads, the starting of the emergency diesel generators, and, when the machines have reached normal speed and voltage, the reconnection of all loads necessary to maintain the plant in a stable hot shutdown condition. If the onsite power sources are not available to re-energize the onsite distribution system, a station blackout (SBO) has occurred.

An electrical distribution system in conformance with GDC 17 was once considered sufficient to ensure that a commercial nuclear power plant would be operated without undue risk to the health and safety of the public. The simultaneous loss of both the offsite and onsite sources of ac power (a station blackout) was considered incredible and therefore did not have to be considered in plant design or accident analysis.

4.8.2 Plant Response

A station blackout is defined as “the complete loss of alternating current (ac) electric power to the essential and nonessential switchgear buses in a nuclear power plant (i.e., loss of the offsite electric power system concurrent with turbine trip and unavailability of the onsite emergency ac power system). Station blackout does not include the loss of available ac power to buses fed by station batteries through inverters or by alternate ac sources, nor does it assume a concurrent single failure or design basis accident”

(10CFR50.2). Because many safety systems required for reactor core cooling, decay heat removal, and containment heat removal depend on ac power, the consequences of a station blackout could be severe.

The immediate consequences of an SBO are not severe if it is not complicated by an accident such as a loss of reactor coolant, steam generator tube rupture, or loss of secondary coolant. If the SBO continues for a prolonged period, the potential consequences for the plant and public health and safety can be serious. The combination of core damage and containment overpressurization could lead to significant releases of fission products offsite. Any design basis accident in conjunction with an SBO would reduce the time to core damage and radioactive release.

The severity of an SBO for a pressurized water reactor (PWR) depends primarily on the combination of the duration of the power outage and the response of the reactor coolant pump (RCP) shaft seals (see Figure 4.8-3). During an SBO, the seals undergo the simultaneous loss of high pressure seal injection and of cooling water to the RCP thermal barriers. With no seal injection, due to the loss of power to the charging pumps, reactor coolant leaks up the RCP shafts. Because the charging pumps are unavailable, this leakage cannot be replaced. The loss of cooling to the RCP thermal barriers, due to the loss of power to the component cooling water pumps, means that the leaking coolant is at very high temperatures. The high temperature leakage can result in degradation of the seals, which might increase reactor coolant leakage up to several hundred gallons per minute. Without systems designed to operate independently of ac power, the only way to mitigate the consequences of an SBO is to minimize the loss of reactor coolant system (RCS) inventory and to quickly restore power to replenish the lost inventory. This will ensure the ability to remove decay heat from the core and to prevent fuel damage.

The severity of an SBO can be mitigated through a controlled cooldown of the RCS. This evolution is covered in the Westinghouse emergency response guidelines (ECA 0.0, "Loss of all AC Power"). The RCS pressure reduction that results from coolant contraction and inventory loss through the RCP seals significantly reduces seal leakage. The cooldown can be maintained as long as natural circulation (or reflux boiling once the system becomes saturated) in the RCS transfers decay heat from the core to the steam generators. The steam generators are available as a heat sink, as long as the power-operated relief valves and steam-driven auxiliary feed pump are available. Manual or local operation of these components may be required to different degrees, depending on specific plant designs. As the RCS pressure is reduced below the pressure of the cold-leg accumulators, they inject borated water to replenish lost inventory. Care must be taken not to let the RCS pressure decrease to the point that nitrogen from the accumulators enters the system. Nitrogen in the RCS could block the flow of water or steam through the steam generator tubes. Another problem associated with the RCS cooldown worthy of consideration is that, as the temperature is reduced, positive reactivity is added to the core due to the moderator temperature coefficient (MTC). Without ac power there is no means to add boric acid to the RCS to ensure an adequate shutdown margin until the accumulators are able to inject, and the potential exists for the core to return to criticality. This concern is most significant at the end of core life, when the MTC is most negative. In addition, the hot reactor coolant leaking from the RCS raises the temperature and pressure of the containment. Without ac power, there is no way to reduce containment temperature, and eventually containment integrity would be lost due to high pressure.

If a cooldown of the plant is not initiated, the loss of inventory through the RCP seals would continue at a high rate, which could even increase due to seal degradation, and eventually result in inadequate core cooling and damage. In either case, core uncovery and loss of containment integrity are inevitable unless ac power can be restored to permit RCS inventory control and containment heat removal.

4.8.3 Regulatory Developments

In 1975, WASH-1400, "Reactor Safety Study," determined that station blackout could be an important contributor to the total risk associated with nuclear power plant core damage initiators. This fact, combined with the increasing indications that onsite emergency power sources (diesel generators [DGs] in most cases) were experiencing higher than expected failure rates, led the NRC to designate the station blackout concern as an unresolved safety issue (USI). By designating the issue as a USI, it would receive priority in terms of study and resolution. USI A-44 was established in 1979, and the task action plan that followed focused on analyzing the frequency and duration of losses of offsite power and the probability of failure of onsite (emergency) ac power sources. Other areas of interest included the availability and reliability of decay heat removal systems independent of ac power and the ability to restore offsite power before normal decay heat removal equipment (equipment that relies on ac power) fails due to a harsh environment. The conclusions of the study would be used as a basis for further rule making and required design changes, if necessary to protect the public health and safety. The results of the station blackout study were published in NUREG-1032, "Evaluation of Station Blackout at Nuclear Power Plants" (June 1988).

Analysis of the reliability and availability of onsite power sources, primarily diesel generators, received the highest priority, because their relative unreliability probably was the deciding factor in designating the issue as a USI. It was felt that, if safety improvements were indeed necessary, it would be more feasible to identify and initiate improvements for onsite power sources than for either offsite power sources or onsite equipment that requires ac power to function. Offsite power source reliability is dependent on several factors, such as regional grid stability, the potential for severe weather conditions, and utility capabilities to restore power, which are difficult to control. Ultimately, the ability of a plant to withstand an SBO depends on the decay heat removal systems, components, instruments, and controls that are independent of ac power.

The SBO concern intensified in 1980 following license hearings for the operation of St. Lucie Unit 2 in southern Florida. The concern was that, with the plant location subject to periodic severe weather conditions (hurricanes) and questionable grid stability, the frequency of losses of offsite power would be much higher than for other plants. The Atomic Safety and Licensing Appeal Board (ASLAB) concluded that a station blackout should be considered a design-basis event for St. Lucie Unit 2. Since the task action plan for USI A-44 provided a considerable amount of time for studying the SBO concern, the ASLAB recommended that plants with station blackout likelihoods comparable to that of St. Lucie be required to ensure that they were equipped and their operators properly trained to cope with the event. NRR changed the construction permit for St. Lucie Unit 2 to include the station blackout in the design basis and required a modification to the Unit 1 design even though preliminary studies showed that the probability of a station blackout at St. Lucie was not significantly different than that for any other plant. Interim steps were taken by NRR to ensure that other operating plants were equipped to cope with an SBO until final recommendations were formulated regarding the USI.

Improvements to the auxiliary feedwater (AFW) system were already being initiated at PWRs, based on the lessons learned from the accident at Three Mile Island. A reliable AFW system with equipment that can operate independent of ac power is very important to the capability for coping with an SBO and for maintaining the plant in a safe shutdown condition.

Recommendations for improvements to emergency diesel generators had already been established, based on studies of DG reliability (NUREG/CR-0660), and were being implemented through licensing requirements for new plants and through technical specification improvements for licensed plants. It was recognized that improving DG reliability was the most controllable factor affecting the likelihood of an SBO and would serve to reduce the probability of occurrence.

Generic Letter 81-04 required licensees to verify the adequacy of or to develop emergency procedures and operator training to better enable plants to cope with an SBO, utilizing existing equipment and expedited restoration of power from either onsite or offsite sources.

4.8.4 French Design

In France, Electricite de France began to study the SBO problem as early as 1977 and has developed plant equipment and emergency procedures to bring a plant to safe shutdown conditions following the loss of all ac power. The 1300-MWe series of plants was originally designed for an SBO, and the 900-MWe series has been improved to meet the more stringent design requirements. Design features that the French have incorporated are shown in Figure 4.8-4. They include multiple turbine-driven emergency feedwater pumps to supply water to the steam generators and a turbine-driven electrical generator that starts automatically and supplies power to vital loads, such as a dedicated RCP seal injection pump to ensure seal integrity and to prevent the loss of RCS inventory. Other loads supplied from the emergency turbine generator include the instrumentation, controls, and lighting necessary to maintain the plant in a safe shutdown condition. The French emergency procedures allow the operators to identify the problem quickly, to maintain the plant in a safe shutdown condition, and to restore power to the unit from either offsite or another unit at the same site as soon as possible.

4.8.5 Station Blackout Rule

Based on the conclusions of the station blackout study published in NUREG-1032, 10CFR50.63, the station blackout rule," was added to the Code of Federal Regulations in 1988. This rule requires that each nuclear power plant be able to withstand for a specified duration and to recover from an SBO. The specified duration is to be based on the redundancy and reliability of onsite emergency ac power sources, the expected frequency of losses of offsite power, and the probable time needed to restore offsite power. The rule further requires that each plant's systems and equipment be capable of maintaining core cooling and containment integrity in the event of an SBO for the specified duration. The capability for coping with an SBO was to be determined by an appropriate coping analysis.

To comply with 10CFR50.63, each licensee was required to submit to NRR the proposed SBO duration for its plant and the justification for its selection, a description of the procedures to be implemented for SBOs, and a list of proposed modifications to equipment and procedures necessary to assure the plant's capability to cope with an SBO for the specified duration.

The station blackout rule also allows a licensee to take credit for an alternate ac source. 10CFR50.2 defines an alternate ac source as an ac "power source that is available to and located at or nearby a nuclear power plant and meets the following requirements:

(1) Is connectable to but not normally connected to the offsite or onsite emergency ac power systems;

(2) Has minimum potential for common mode failure with offsite power or the onsite emergency ac power sources;

(3) Is available in a timely manner after the onset of station blackout; and

(4) Has sufficient capacity and reliability for operation of all systems for coping with station blackout and for the time required to bring and maintain the plant in safe shutdown...."

The station blackout rule states that an alternate ac source constitutes acceptable capability to withstand an SBO provided that the licensee performs an analysis which demonstrates that the plant has this capability, that the licensee demonstrates by test the time required to start and align the source, and that the alternate ac source meets certain capacity requirements. If the alternate ac source meets those requirements and can be demonstrated to be available to power the shutdown buses within 10 minutes of the onset of an SBO, then no coping analysis is required.

Regulatory Guide 1.155, "Station Blackout," also issued in 1988, provides guidance for meeting the requirements of 10CFR50.63. The guide contains guidance on:

- Maintaining an individual emergency diesel generator target reliability of 0.95 or 0.975 per demand and assumes that, as long as the unavailability of DGs due to maintenance and testing is not excessive, the maximum DG failure rate would result in overall reliability for the emergency power system;
- Establishing a DG reliability program with test, maintenance, data collection, and management oversight elements to maintain the selected DG target reliability;
- Developing procedures and training to cope with an SBO;

- Selecting a plant-specific minimum acceptable blackout duration capability of 2, 4, 8, or 16 hours based on the reliability and redundancy of onsite emergency ac power sources, the expected frequency of losses of offsite power based on the independence of offsite power sources and the plant's susceptibility to severe weather, and the probable time needed to restore offsite power;
- Evaluating a plant's capability to cope with a blackout based on the selected duration capability; and
- Completing modifications as necessary to cope with a blackout.

The guidance is structured so that the lower emergency diesel generator target reliability (0.95) is selected at plants where the DGs are demonstrated to be relatively unreliable, and that longer blackout coping durations are selected at plants with relatively unreliable DGs and at plants that are more susceptible to losses of offsite power.

All licensees have completed actions to comply with the station blackout rule. As a result of the rule, all plants have established blackout coping and recovery procedures, completed training in accordance with these procedures, established emergency diesel generator reliability programs which have improved DG reliability, ensured a four- or eight-hour coping capability, and implemented modifications as necessary to cope with an SBO. Modifications include additional DGs (some as onsite emergency ac power sources and some as alternate ac sources); modifications to existing DGs and DG auxiliaries; the addition of or modifications to gas turbine generators, added cross-ties between buses, units, and power sources; and changes to dc load-shed procedures.

In accordance with the regulatory assessment requirement of the station blackout rule, the NRC has completed safety evaluations of licensee compliance actions for all plants. In addition, the NRC completed eight pilot inspections prior to 1995 to verify the adequacy of licensee programs, procedures, training, equipment and systems, and supporting documentation in implementing the station blackout rule. Because these inspections found only minor problems, the NRC staff concluded that additional inspections to verify adequate implementation of the rule were unnecessary.

4.8.6 PRA Insights

4.8.6.1 Historical

Because of the dependence on electrical power by most of the systems involved in the mitigation of accidents, the electrical distribution system can be a major contributor to core damage frequency. This was first made evident in WASH-1400. SBO sequences account for greater than 10% of overall plant core damage frequency for 45 of 69 operating pressurized water reactors. According to NUREG-1560, "Individual Plant Examination Program: Perspectives on Reactor Safety and Plant Performance" (1997), the most influential factors on SBO-attributable core damage frequency for Westinghouse plants are the number of emergency ac power sources, battery depletion time, how coolant losses due to RCP seal failure are modeled, and whether modifications such as RCP seals with high-temperature o-rings or the provision of alternative seal cooling have been made.

A major accident sequence has a station blackout as the initiator, followed by RCP seal failure, leading to a small-break loss of coolant accident. This sequence leads to core damage because of the unavailability of the high pressure injection system for replenishing the reactor coolant inventory.

Other sequences involving electrical power problems as initiators involve the failure of the auxiliary feedwater system, the failure of a pressurizer power-operated relief valve (PORV) to shut, and the failure of a PORV to open to enable bleeding and feeding. Causes of loss of power initiators include:

1. The failure of DGs to start,
2. The failure of DGs to run after starting,
3. The failure to recover ac power,
4. The unavailability of DGs due to testing or maintenance, and
5. A local inverter fault which fails the automatic actuation of the auxiliary feedwater system.

A report prepared by the NRC Office of Nuclear Regulatory Research, "Final Report: Regulatory Effectiveness of the Station Blackout Rule" (2000), assesses whether the station blackout rule has been effective in achieving the desired outcomes. The report concludes that, although there are opportunities to clarify SBO-related regulatory documents, the rule is effective, and industry and NRC costs to implement the rule were reasonable. The report provides the following detailed conclusions:

- The reduction in the mean SBO-attributable core damage frequency was approximately 3.2E-05/RY, slightly better than the expected 2.6E-05/RY. As a result of improvements made to address the station blackout rule, more plants achieved a lower SBO-attributable core damage frequency than expected, and the plants with the greatest numbers of losses of offsite power from plant events and extremely severe weather conditions made the largest improvements, most by providing access to alternate ac power supplies. In addition, with some exceptions, the observed DG reliability performance exceeds the mean DG reliability assumptions of probabilistic risk assessments and individual plant examinations, indicating that SBO-attributable core damage frequencies are smaller than those stated in those risk assessments. As the blackout rule risk reduction objectives have been exceeded, further investigation of strategies for reducing SBO frequencies may not be needed.

- Before the blackout rule was issued, only 11 of 78 plants surveyed had a formal emergency DG reliability program, 11 of 78 plants had a unit average DG reliability of less than 0.95, and 2 of 78 had a unit average DG reliability of less than 0.90. Since the blackout rule was issued, all plants have established DG reliability programs which have improved DG reliability. Only 3 of 102 operating plants have a unit average DG reliability of less than 0.95, considering actual performance on demand and unavailability due to maintenance and testing with the reactor at power. However, unavailability due to maintenance and testing at power is greater than expected and explains why licensees appear to be having difficulty meeting the 0.975 target reliability. Decreased DG reliabilities and/or increased maintenance and testing unavailabilities erode the risk benefits obtained from implementing the blackout rule.

- Operating experience indicates that modifications implemented in response to the blackout rule have increased defense in depth against power interruptions. Turkey Point's ability to ride out Hurricane Andrew in 1992 illustrates this point; there is some likelihood that the plants would have lost all ac power during a 2.5-hour interval a few days after the storm without two emergency DGs added to address the blackout rule. Blackout-rule modifications also provide defense in depth to compensate for potential degradation of offsite ac power sources that may result from deregulation of the electric power industry or longer-than-expected times for recovery of offsite power following extremely severe weather.
- A value-impact analysis indicates that the rule's outcome was within the expected range of reductions in public dose per dollar of cost. Not expected was the addition of 19 power supplies at a cost of $174M. However, the addition of power supplies has resulted in significant plant-specific reductions in core damage frequency and has provided significant monetary benefits associated with greater operating flexibility resulting from longer allowed outage times for DGs.

4.8.6.2 Plant Event

In March of 1990, Vogtle Unit 1 experienced a loss of all ac power for a period of approximately 36 minutes. The blackout was caused by a combination of human errors and equipment failures.

Prior to the loss of power, the plant was shutdown with the reactor vessel head installed, but with the head bolts de-tensioned. The reactor coolant system was drained to mid-loop for maintenance. Train A of the residual heat removal system was maintaining primary temperature. The B diesel generator was disassembled for maintenance, and the B reserve auxiliary transformer (RAT) was tagged out for maintenance. Offsite power was being supplied by the A RAT.

At approximately 9:20 a.m., a truck toppled a tower onto the A RAT, causing a loss of offsite power to Unit 1. The A diesel generator started but did not continue to run. The diesel trip signals were bypassed, and the diesel was emergency started at 9:56. During the period when ac power was not available, the reactor coolant system temperature increased by 46°F (an equivalent heatup rate of 1.3°F/min). After power was restored, the A train of the residual heat removal system was restarted to reduce the primary temperature.

The Vogtle station blackout occurred after the plant had been shut down for a period of time, so the decay heat level was very low. Had the blackout initiated with a larger decay heat load, the rate of temperature increase would have been much faster. In this case the shutdown plant conditions and the short duration of the blackout minimized the consequences of the event (RCP seals were not threatened). Nevertheless, the Vogtle Unit 1 blackout was very similar to core damage sequences which appear in plant

PRAs, and more severe initial conditions or a longer blackout duration could have resulted in core damage.

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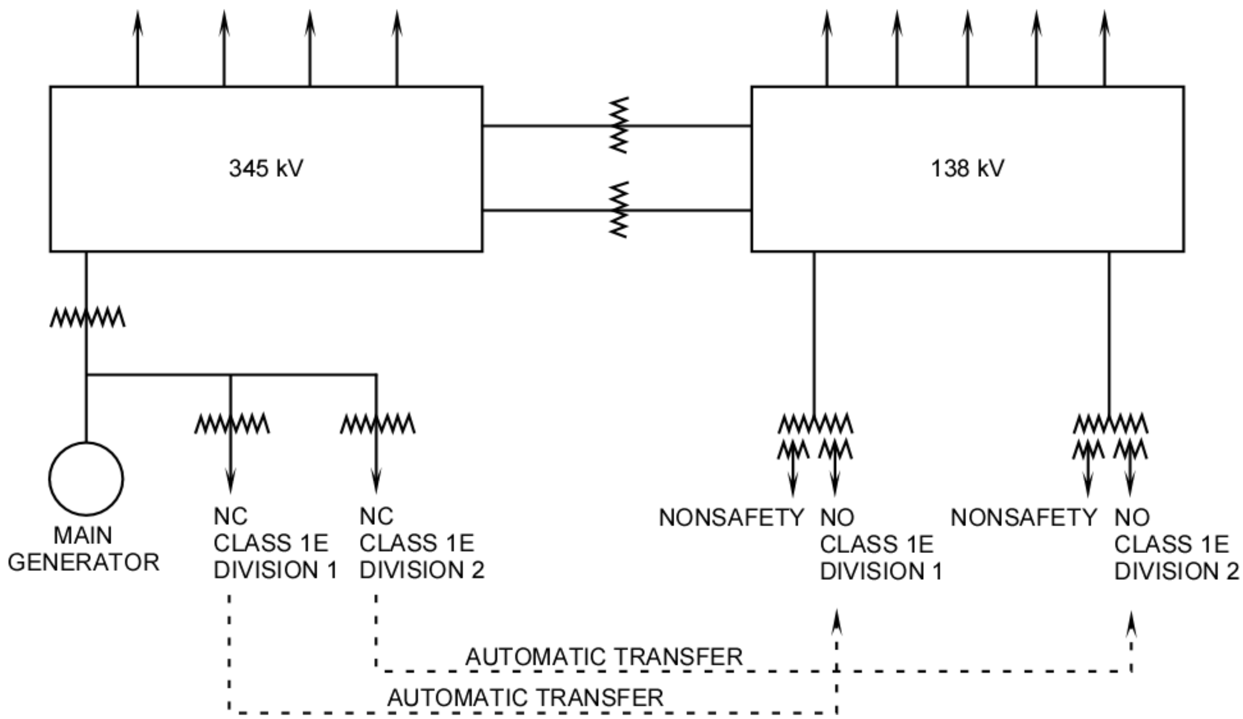

Figure 4.8-1 Typical Offsite AC Distribution

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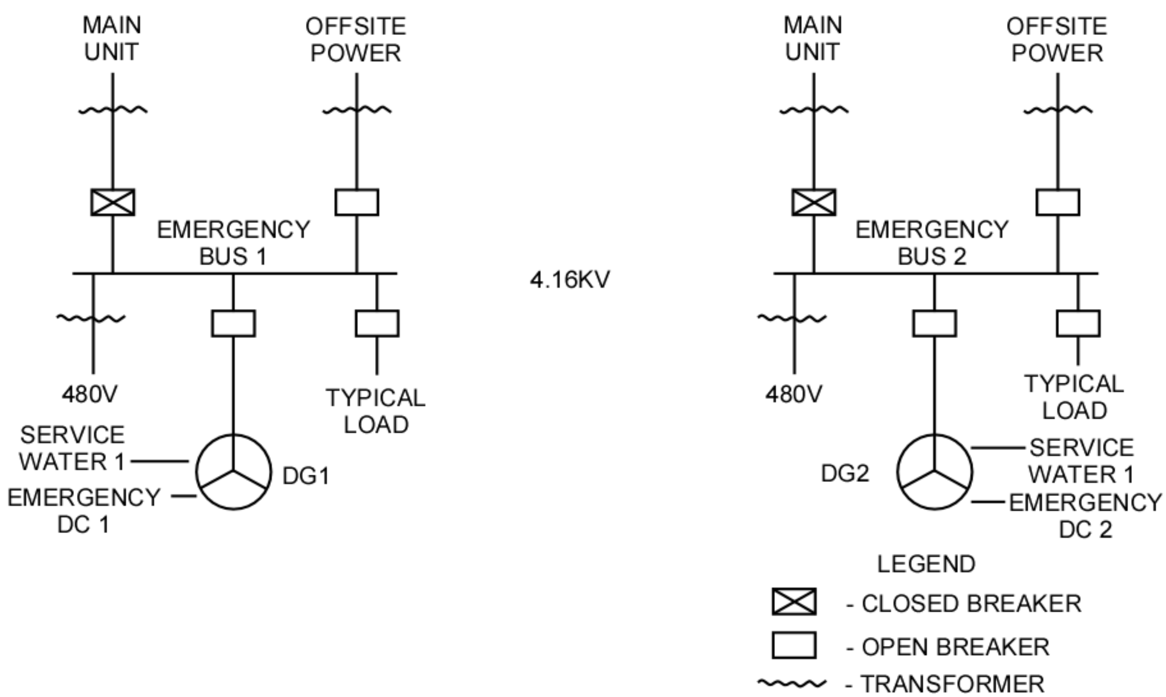

Figure 4.8-2 Typical Onsite AC Distribution System

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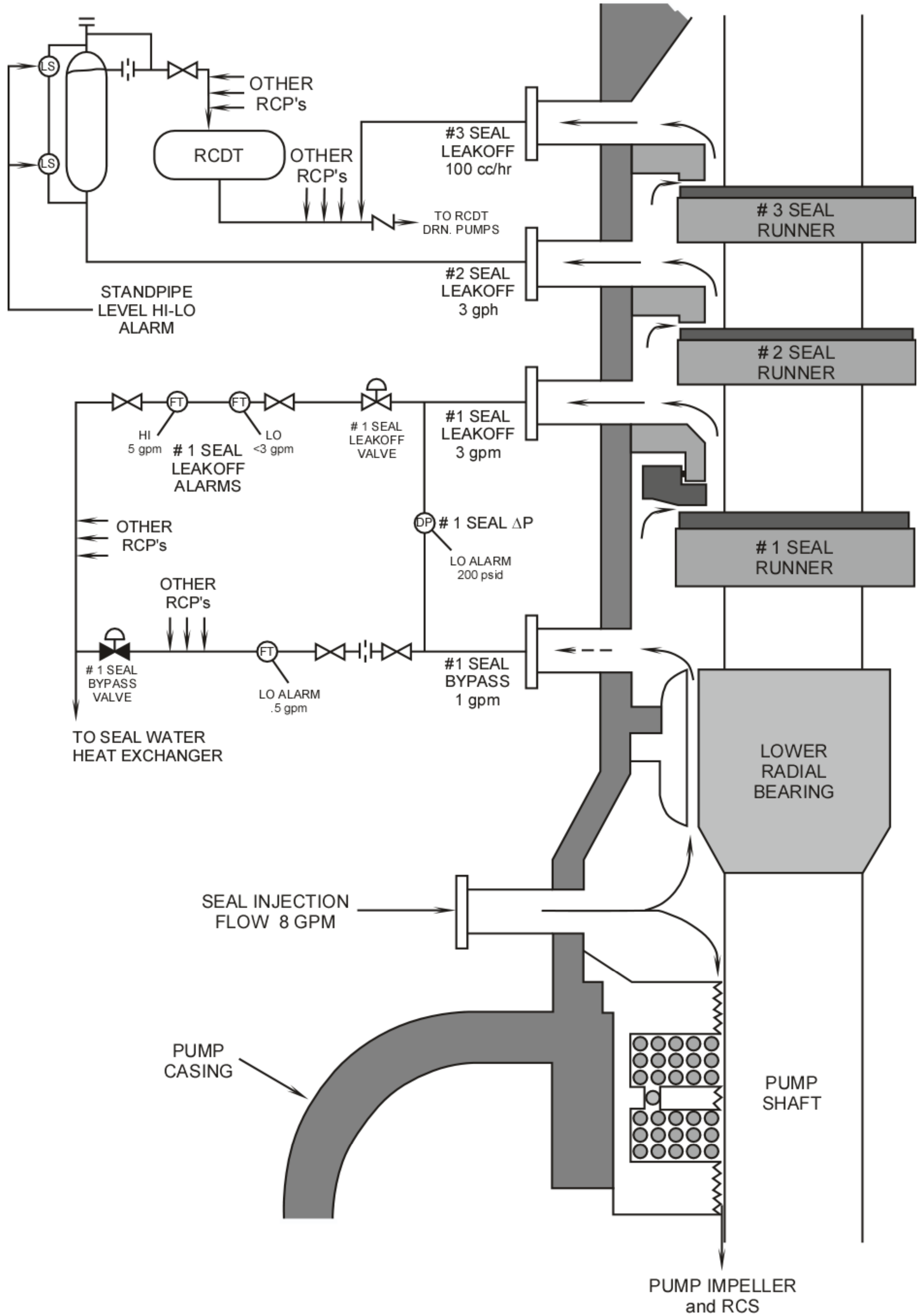

Figure 4.8-3 Seal Flow Diagram

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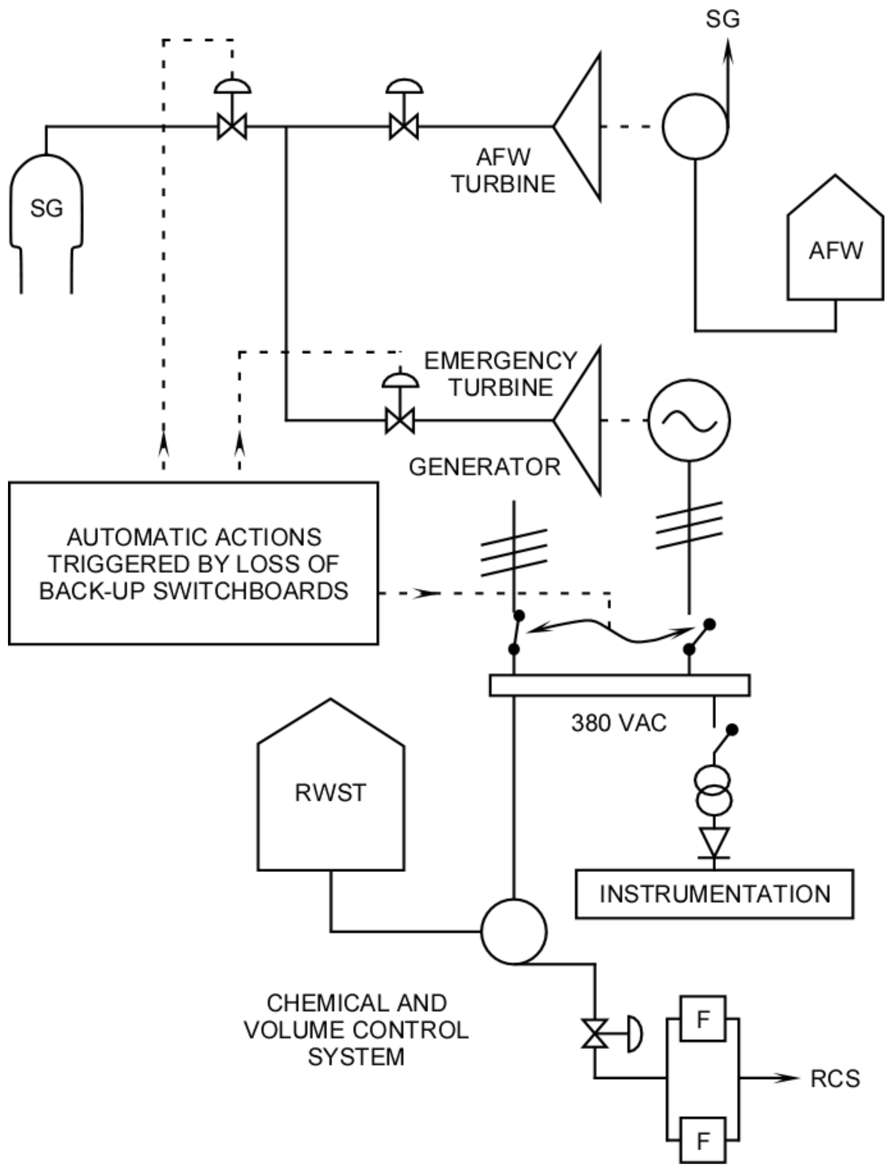

Figure 4.8-4 French Design for Safe Shutdown During a Blackout

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